AG-81

PART II

DIRECT ENERGY CONVERSION THERMAL SOURCES

SECTION A

ENERGY SOURCES

NUCLEAR SOURCE LIMITATIONS FOR DIRECT CONVERSION DEVICES

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Nuclear energy sources from solid-fuel fission reactors to eventual fusion reactors are considered for application to direct conversion. Brief review of system operating requirements provides a background for assessment of the potentialities and inherent physical limitations of these sources for direct conversion. Emphasis is placed on the characteristics of solid-fuel and gaseous-fuel fission reactors for application to thermionic and MHD conversion systems.

Upper limits of operating temperature are shown to range from 2700°C *to* 3700°C *with the best solid fuels (U-loaded* C *to* TaC *and* HfC) *thus allowing Carnot cycle efficiencies of* 50 *per cent to* 65 *per cent to be considered for space applications and* 80 *per cent to* 90 *per cent for ground applications. For the former it is more important to achieve high cycle efficiency relative to Carnot efficiency than for the latter class of systems. The advantages of high-temperature source operation are negated unless high relative efficiency is achieved.*

Analysis of gaseous-fuel plasma production shows that the upper limit temperature capability depends upon the type of conversion cycle of interest (i.e. continuous flow vs pulsed operation), and that thermal radiation from the plasma becomes the dominant irreversible loss mechanism at extreme temperatures. Typically, peak temperatures of 10,000°K *to* 40,000°K *may be attainable. These potential upper limits are so high that Carnot efficiencies in the order of* 90 *per cent are available, thus the principal problem of achieving high over-all conversion efficiency rests with the choice of conversion cycle. In this circumstance it is difficult to separate the "limitations of nuclear sources" from those inherent to the operating cycle; an integrated systems view is required to achieve maximum over-all performance.*

The power densities which characterize operation at these extreme temperatures are so high that systems of minimum feasible working size (from the standpoints of nuclear criticality and non-excessive losses) must operate at thermal power levels of several tens of megawatts and above. Conversely, solid-fuel nuclear sources can be used effectively in conversion systems of a few tens of kilowatts (thermal).

The eventual development of fusion reactors does not promise greater efficiency than from gaseous-fuel fission systems (again this depends almost entirely on the conversion cycle chosen) but simply changes the temperature levels of operation to much higher values (ca. 10 kev–10^8 °K). *This has the consequence that minimum practicable system thermal power levels may be several hundreds to thousands of megawatts.*

Les sources d'énergie nucléaire, des réacteurs à fission de combustible solide aux réacteurs à fusion sont étudiés en vue de leur application à la conversion directe. Un bref rappel des conditions de fonctionnement des divers systèmes constitue une base d'évaluation des possibilités et des limites d'utilisation des générateurs nucléaires pour la conversion directe. L'auteur insiste particulièrement sur les caractéristiques des réacteurs à fission de combustible solide ou gazeux favorables à leur emploi dans les systèmes de conversion thermoionique ou MHD.

Il est montré que les limites supérieures des températures de fonctionnement se situent entre 2700 *et* 3700°C *pour les meilleurs combustibles solides* (C *chargé en* U, TaC *et* HfC), *ce qui permet d'envisager des rendements du cycle Carnot de* 50 *à* 65 *pour cent pour les applications spatiales et de* 80 *à* 90 *pour cent pour les applications terrestres. Pour les applications spatiales, un rendement élevé cycle par rapport au rendement Carnot est plus important que pour les autres. Les avantages que confère le fonctionnement de la source à des températures élevées sont annulés si l'on n'obtient pas un fort rendement relatif.*

L'étude de la production de plasma par l'emploi de combustibles gazeux montre que la limite supérieure de température dépend du cycle de conversion choisi (à flux continu ou pulsé) et que le rayonnement thermique du plasma devient la cause prépondérante de pertes irréversibles aux températures limites. Des crêtes de températures de 10,000 *à* 40,000°K *peuvent souvent être obtenues, températures si élevées que l'on dispose de rendements Carnot de l'ordre de* 90 *pour cent et que le problème essentiel d'un haut rendement global est une question de choix du cycle de conversion. Il est malaisé ici de faire la distinction entre les "limites des sources nucléaires" et celles qui sont inséparables du cycle d'opérations et il faut se livrer à des considérations d'ensemble pour obtenir la meilleure performance globale.*

Les densités de puissance caractérisant le fonctionnement à ces températures limites sont si élevées que des systèmes de dimensions aussi réduites que l'autorisent les considérations relatives au processus nucléaire et à la limitation des pertes doivent fonctionner à des niveaux de puissance thermique de plusieurs dizaines de mégawatts et au-dessus. Par contre, des sources nucléaires à combustible solide peuvent être employées avec succès dans des systèmes de conversion de plusieurs dizaines de kilowatts (thermiques).

La mise au point possible de réacteurs à fusion ne permet pas d'espérer un rendement supérieur à celui des systèmes à fission de combustible gazeux (comme il a déjà été dit, celuici dépend presque exclusivement du cycle de conversion choisi), mais elle aura pour effet de porter les températures de travail à des niveaux plus élevés (10 kev *soit environ* 10^8 °K). *Il en résulte que la puissance thermique minimale d'un système d'application pratique peut se situer entre plusieurs centaines et plusieurs milliers de megawatts.*

INTRODUCTION

In attempting to assess the possibilities for and limitations of nuclear energy sources for use in direct conversion devices designed to transform thermal to electrical energy, we find immediately that the characteristics and features of the conversion cycle must be considered for a realistic assessment. Accordingly first we survey conversion cycles of potential interest, and next review the physical limits on the basic nuclear sources alone. Finally, by combination of the limiting characteristics in each area, we identify several source/converter systems which may typify the "fundamental" upper limits on performance of nuclear sources for direct conversion.

SURVEY OF ENERGY CONVERSION SYSTEMS

Systems Using Conversion External to the Source

If the energy conversion equipment is separated from the nuclear source it is possible to decouple the mutual interaction between these items. Turbomachinery systems (such as mercury vapor-turbine/compressors) exemplify one class of external converters; these are considered in detail elsewhere in this symposium (Ref. 1). External direct converters of interest for limit-study application are restricted to high-temperature plasma devices —thermo-electric converters operate at temperatures too low to define upper limits on source capabilities. Two such external-converter devices are of special interest:

1. Plasma thermionic converters (Ref. 2) and;
2. Hydromagnetic ($\bar{j} \times \bar{B}$) converters (Ref. 3).

By definition, the use of external converters implies source/converter energy transfer; this can be accomplished (conceptually) either by a working fluid or by thermal radiation. Plasma thermionic converters (hereafter called PTC) operate best at emitter temperatures above 2000°C, thus require source temperatures above this level. Since a PTC requires material surfaces for electron emission and collection, it is inherently temperature-limited by the materials technology of its emitting surface structures. Principles, limits, and details of such devices are discussed in (Ref. 2) cited above.

Upper limits on materials for PTC applications seem to be at the strength/limit temperatures of solid materials: Estimates for some of these are listed in Table 1 for a variety of PTC materials of interest. If energy transfer from source to converter can be made efficient (i.e. with small temperature differences) then the same limits apply to the source, and solid materials can be utilized for nuclear fuel structure. At higher temperatures all fuels become liquid and energy transfer must be by thermal radiation if PTC limits are not to be exceeded.

Hydromagnetic converters (discussed in detail in Ref. 3) and hereafter denoted as HMC) must operate at temperatures well above those of PTC materials for most efficient conversion. Typically a HMC transforms the kinetic energy of a stream of hot ionized gas into electrical energy by induction of currents in the passage of the plasma through an external magnetic field. Because the plasma must flow between bounding walls and for most efficient operation must be hotter than solid materials can tolerate, the limiting condition here is wall cooling. Without a careful analysis of the converter wall heat loads and cooling capability in the system we cannot cite defensible numerical values for upper temperature limits. The values given in Table 1 are only approximate but do indicate the general range of interest. The source which provides the best hot plasma cannot be solid, thus the nuclear fuels used in such a system (at conditions of greatest conversion efficiency) must be either in the liquid or gaseous state. In fact, the plasma itself may be formed from the fissionable fuel in a gaseous core reactor system (see below). Solid-fuel-heated plasmas may also be considered but are not of interest in assessing *upper* limits on nuclear sources for direct conversion.

Table 1. Plausible Upper Limiting Temperatures of Nuclear Sources for Use in Several Direct Conversion Systems

Source	Conversion system[a]		
	PTC	*Linear HMC*	*Oscillatory HMC*
Solid fuels			
graphite	2700°C	2700°C	—
carbides	3500°C	3500°C	—
Liquid fuel			
carbides	3500°C	3700/4500°C	—
Gaseous fuel			
fission	—	4000/6000°C	$1-3 \times 10^{4}$ °C
fusion	—	—	$\sim 10^{8}$ °C

[a] See text for definition.

Systems Using Direct Conversion in the Source

Integrating the source and converter functions allows a simple assessment of limit conditions; these become simply and directly the limits on the nuclear energy sources themselves. Here two classes of direct conversion systems appear of greatest interest for our purposes. One of these is the PTC, discussed above, which again is limited to temperatures of solid or liquid fuels. The second class of converters are those based upon an oscillatory type of HMC, in which plasma is formed, heated, and caused to expand and contract within a cyclic time-varying, externally-imposed magnetic field structure. Such systems have been proposed and analyzed elsewhere for both fission fuel sources (Refs. 4 and 5) and fusion (Ref. 6) power conversion. As for the externally operated HMC system, above, true temperature limits here are set by wall cooling requirements. However, the plasma may be made to pulsate radially in a spherical or long cylindrical configuration throughout its cycle and may be kept away from structural walls by the use of magnetic fields, thus the upper limit temperature potentially is higher than that for the linear flow HMC system described previously. The values listed in Table 1 are only roughly indicative of the potential range of such internal direct conversion systems.

We later consider two of these systems in more detail.

SURVEY OF NUCLEAR SOURCE LIMITS

Solid Fission Reactor Fuels (3000/4000°K)

The choice of materials for use in ultra-high-temperature fuel elements is extremely limited. Only carbon (graphite, C) tungsten (wolfram, W) and rhenium (Re) appear to be useful among the elements, and the compounds of most potential value appear to be the carbides of tantalum (Ta), niobium (Nb), and zirconium (Zr). Some data on these materials are given in Table 2, together with estimates of potential performance levels. Hafnium carbide, often proposed for high-temperature fuel elements, has such very undesirable nuclear properties that we exclude it from consideration.

Except for graphite little is known of the effect of addition of fissionable fuel to these materials, but it is unlikely that marked changes in physical properties will occur if fuel loadings are held to a few percent by volume or less. With respect to the carbides, however, it is reasonable to assume that large fractional concentrations of fuel will reduce melting points toward those of the uranium carbides used as the fuel carrier. Since these are about 2450°C, 2300°C, and 1800°C for UC, UC_2, and U_2C_3, respectively, we see that much of the potential temperature advantage over graphite of the higher-melting-point carbide base materials will be lost unless reactor designs can be devised which allow use of lightly loaded carbide fuel elements. For use of graphite, experimental studies reported at the 1958 Geneva Conference have shown that the addition of uranium (as carbides) to a graphite matrix causes only a modest reduction (less than 20 per cent) in short-time breaking strength for uranium loadings as high as 0·35 gm U/cm^3 of graphite.

All of the elements and compounds listed above (except graphite) are probably capable of operation within about 200°C of the listed melting points provided that: (1) Fissionable fuel concentration is kept very low (i.e. a few percent) and; (2) Reactor design is such that load stresses are small (order of 10^7 dynes/cm^2–150 lb/in^2). For use of the carbides, compressive rather than tensile loading may be necessary.

Thermal neutron capture cross-sections indicate the relative competition for thermal neutrons offered by the fuel element base material and thus are of interest in comparisons of materials for use in predominantly thermal reactors. The resonance absorption integral is a measure of the neutron absorption probability for neutrons slowing down from fission energy to thermal. Taken together these two nuclear characteristics help to define the relative merits of the different materials listed, for use in reactors of any given neutron spectrum. We note that the macroscopic thermal capture cross-sections of Ta and W are about 3000 times that for C, whereas that for Re is some 1500 times higher. Further W, Re, and Ta all have resonance absorption integrals so large that it is not practical to consider these materials or their carbides for use in regions of large epithermal neutron flux. Neutronically efficient use of these materials requires either use in completely fast reactors where few epithermal neutrons are present, or lumping of structure in a moderating matrix core so that neutron slowing-down can occur in regions away from these resonance absorbers. A reactor is "fast" only if little neutron slowing-down can take place in the size and materials mixture chosen. Heavy elements such as those discussed above are very poor moderators, thus are well suited for use in fast reactors. However because fission cross-sections for fast neutrons are of the order of one-hundredth of those for thermal neutrons the fissionable fuel density required for criticality in such systems is inherently very much larger than is needed in thermal reactors. Because of this the fissionable fuel concentrations required for criticality are always so large that the upper limiting temperature of loaded fuel elements for fast reactors are very much less than those listed in Table 2 for the base materials alone. Figure 1 gives an approximate, semi-quantitative indication of the probable temperature limits for use of uranium carbide

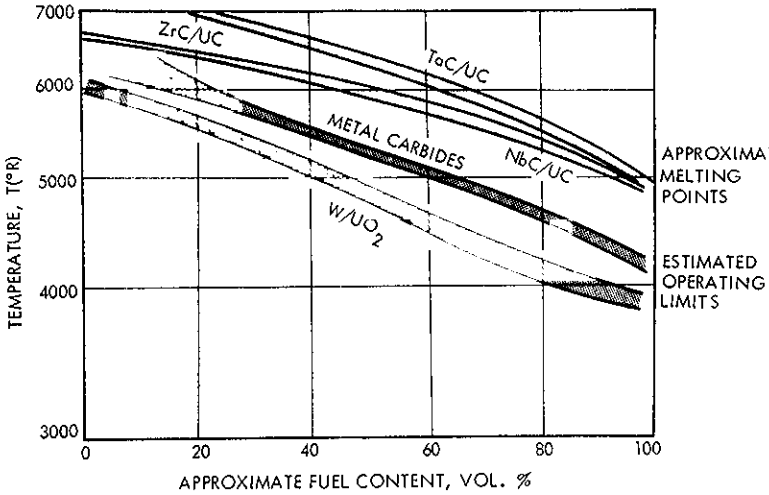

Fig. 1. Probable practical limits on superheater nuclear fuel sources.

fuel in other metallic carbides and for uranium oxide in a tungsten structural base. We will return to this information later in connection with "superheater" reactor concepts.

Use of moderating matrix geometry to get around the poor neutronic properties of W, Re, and Ta provides a partial solution but also suffers from difficulties in application. In order to allow neutron thermalization in regions relatively free of epithermal absorption the major part of the reactor volume must be taken up by non-fissioning moderator volume. The power density in the remaining small fractional volume allotted to the fuel elements must therefore be very much larger for the same over-all reactor size than if all of the core were useful as a heat exchanger. And, as before, uniform fuel loading of all of the prime fuel element material leads to a lower temperature capability than that of the base material alone.

Liquid Fuels (3500/4500°K)

The next step beyond solid sources is to use fuels in the liquid state. The liquid fuel chosen should be capable of operation at a temperature as high as possible yet must be molten at temperatures below the softening point of the best solid materials in order to permit its containment by solid structures. Thus the spread between melting and boiling points should be as large as possible. Furthermore the liquid base must be able to contain fissionable material in fairly uniform solution to avoid the problems of separation of immiscible fluids. A brief review of available data shows several fuel combinations which appear promising for such use. Mixtures of uranium carbide with tungsten or zirconium carbides can operate up to about 4400°C. At this point the uranium carbide will begin to boil (at 1 atm) out of the mixture. Tungsten carbides melt at 2600° to 2800°C,

Table 2. Some Properties of Fuel Element Base Materials

Materia	*Graphite* (C)	*Tungsten* (W)	*Rhenium* (Re)	*Tantalum carbide* (TaC)	*Niobium carbide* (NbC)	*Zirconium carbide* (ZrC)
Melting point, °C	3650 (sublimes)	3370	3170	3900	3500/3600	3500/3600
Room temperature density, gm/cm³	1·67/1·85	19·2	20·5	14·7	7·8	6·7
Thermal conductivity at 2500 °C, watts/cm °C	0·17/0·35	0·86	—	0·23[a]	0·15[a]	0·21[a]
Thermal neutron absorption cross-sections (Microscopic, barns/atom)	0·0045	19·2	84	21·3	1·15	0·185
Resonance absorption integral (barns/atom)	0	450	650	550	4	3

[a] At 20°C.

thus fuels based on this material can be contained within shells of tungsten metal or graphite, unless excessive corrosion takes place at the liquid-solid interface; unfortunately little is known on this point. Zirconium carbide, with a melting point of 3500°C, is very difficult to contain in molten form; however lower melting points can be obtained by mixture with uranium carbide. The melting point of pure UC_2 is about 2300°C, thus this can be used alone as a liquid fuel if sufficient fuel volume for heat transfer purposes can be obtained without dilution. However, dilution may be useful to reduce fuel vapor losses during reactor operation.

Use of these fuels for high-power density heating requires bubbling the coolant gas through the hot liquid fuel. To conserve fuel material or to prevent its entrainment with the flowing gaseous coolant some method must be found to ensure separation of liquid from the gas before this is delivered to the conversion system. In principle this can be achieved by use of the centrifugal forces resulting from rotation of a cylindrical core. The core fuel region could be rotated mechanically or by tangential injection of coolant gas, which would also serve to establish a radial temperature gradient in the molten fuel and keep the container walls cool. If bubble sizes are kept small the gas temperature at exit from the fuel inner face can be made very close to the peak fuel temperature. Core rotation at a few hundred revolutions per minute is sufficient to stabilize the shape of a thin region (order of several cm thick) of liquid fuel without producing excessive hydrostatic pressures at the fuel outer radius. None of the liquid fuels mentioned is capable of much neutron moderation; however, criticality can be achieved by using thick external reflectors of Be, C, or D_2O. The reflector material need not rotate with the core for stability of the fuel region. The maximum temperature

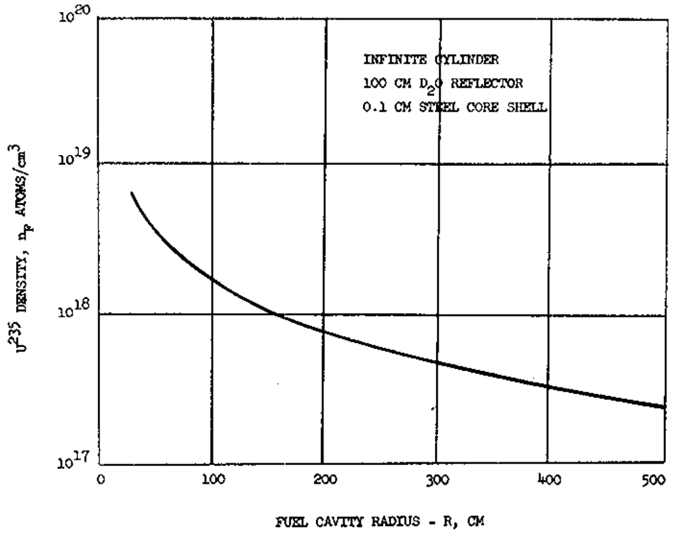

Fig. 2. Criticality in gas core reactors.

gain potentially possible from use of liquid fuels is about 1000°C above the limit of solid core reactors.

Gaseous Fission Plasmas

In principle a gaseous fission plasma can be made to operate at arbitrarily high temperature. In practice the temperature is constrained by two physical processes. The most compelling of these is the necessity of achieving nuclear criticality if we are to have a source at all. Figure 2 shows the requirements on nuclear fuel density n_F, for criticality in a single large cavity surrounded by a thick shell of good neutron moderator (e.g. D_2O or Be) as a function of the radius R_c of the gas-filled cavity. If we now apply a constraint that the system pressure be limited to a fixed value, say P_c, then the maximum possible operating temperature T_m will be fixed by the gas law $P_c = n_F k T_m$. Using this we derive Fig. 3 which shows the allowed T_m versus R_c.

The second physical constraint on temperature arises from a combination of nuclear and thermodynamic efffects. Suppose our gaseous core is spherical and fills the cavity when it is at maximum temperature. At this condition it is radiating thermal energy directly to the walls at T_w at a rate q_r^+ given by the usual Stefan-Boltzmann law $q_r^+ = \bar{\varepsilon}\sigma(T_m^4 - T_w^4)$. Here the emissivity $\bar{\varepsilon}$ is an effective value characterizing the plasma density and dimensions of concern. Saenger (Ref. 7) has computed the approximate emissivity of uranium plasmas over a wide range of conditions of temperature, pressure, and plasma thickness. From this he was able to calculate the power

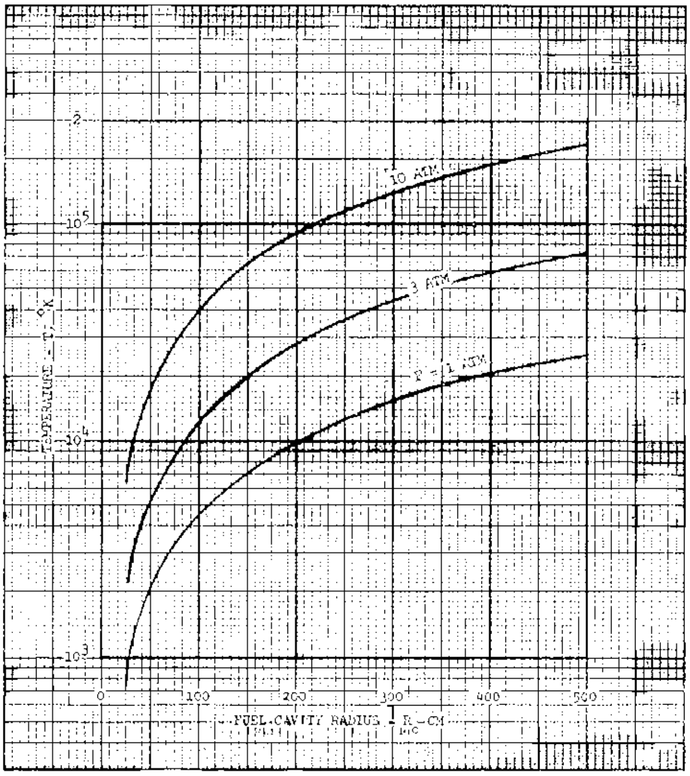

Fig. 3. Critical temperature in gas core reactors.

radiated from the plasma surface, assuming that $T_w \ll T_m$. Results of this work, corrected to account for an error in the original calculations*, are given in Fig. 4. Now, for any given wall cooling capacity (i.e. coolant heat flux capability q_c) Fig. 4 shows the maximum allowable temperature of a plasma-filled cavity. This, in turn, leads to a minimum size of plasma (at fixed pressure), from the criticality considerations of Fig. 3. For example, for an assumed maximum practically attainable cooling of $q_c \simeq 100$ kw/cm^2 and a pressure of 3 atm we see that $T_m = 18{,}000$°K and $R_c \simeq 130$ cm.

* Pointed out at the Conference by Prof. T. Peters of the Forschunginstitut für Physik der Strahlantriebe, Stuttgart, and Dr. R. Pruschek of the Technische Hochschüle, Munich.

The actual situation in a pulsing-plasma-core direct conversion reactor is more complex than this. Even so, we see in this simple illustration the strong inter-relation of conversion cycle parameters and source operating conditions in setting the nuclear source limitations for direct conversion. We consider the more complicated pulsating system in further detail below.

Fusion Plasmas

Here, as above, electrical power production directly requires oscillating or pulsating plasma motion within time-varying magnetic fields. Unlike the gaseous fission reactor, ultra-high temperature is essential to the achievement of fusion in the first place. This is because a sustained thermonuclear

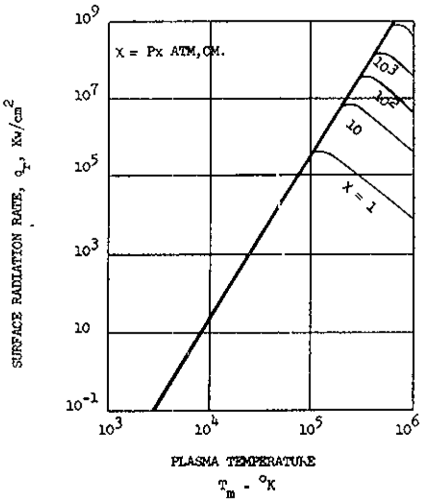

Fig. 4. Thermal radiation from uranium plasma Ref. (7).

reaction can proceed in a mass of fusible gas only if the random energy of gas plasma ions (i.e. the temperature) is large enough that binary collisions can overcome the Coulomb barrier between each ion-pair. The temperature at which this occurs for deuterons (D) is the order of 10^8 °K (*ca.* 10 kev). At such temperatures, the gas law allows only very low density for reasonable pressures. In order to reduce wall heat transfer losses fusion machines employ (conceptually) magnetic fields to confine the plasma. Power losses, which set the limiting operating conditions, then involve mechanisms other than ion diffusion to and collision with the walls. Even in the absence of such particle transfer, losses due to electromagnetic radiation from gyrating ions in the confining field provide limits on operating conditions. These "cyclotron radiation" losses (first analyzed extensively by Trubnikov (Ref. 8)) become larger with larger fields, hotter gases, and (because of reduced self-absorption) with smaller-size plasmas. In addition, similar radiation losses arise from electron acceleration in electron/ion collisions within the plasma. These "bremsstrahlung losses" increase with increasing ion charge number and plasma density. Thus, there are loss mechanisms which bound the operating temperature from above and nuclear fusion requirements which bound it from below. The whole problem is very complex, but is surveyed concisely by Saxe (Ref. 9). Figure 5 shows a power balance for hypothetical fusion reactors (none exist at present) as a function of temperature, for plasma dimensions covering a range of mean free paths

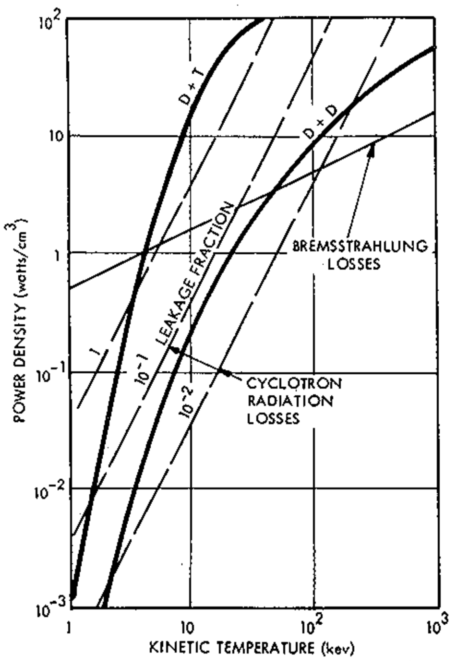

Fig. 5. Power balance for fusion reactors.

for absorption of cyclotron radiations. From this we see that fusion devices operating on $(D + T)$ must always operate near 5–50 kev while $(D + D)$ systems require still higher temperatures, *ca.* 50–500 kev. In the latter case, useful net power can be produced only if the plasma is greater than about 5 mean free paths thick. Power losses (and consequent wall heat flux loads) will be set almost entirely by choice of system size, with large systems favored for low heat fluxes.

POTENTIALITIES AND CHARACTERISTICS OF TWO SPECIFIC SYSTEMS

Advanced Solid-Fuel Fission Reactors

We have discussed earlier the temperature capabilities of various base materials useful as fuel carriers and those of potential fuel compounds for high-temperature use as well. As pointed out, the addition of fissionable fuel to the most promising high-temperature base materials will severely restrict the operating temperature of the combination. Only if some way can be found to use very light loading (e.g. under a few percent) with fuel compounds will it be possible to achieve the full potential of the base material.

Graphite, which has a low atomic mass and good high-temperature properties, is ideally suited for use as a self-moderating fissionable fuel carrier. However, strength data indicate that a practical upper temperature limit for its use in rocket reactors is about 2600° to 2700°C. To achieve higher core temperature use must be made of the carbides listed in Table 2 in such

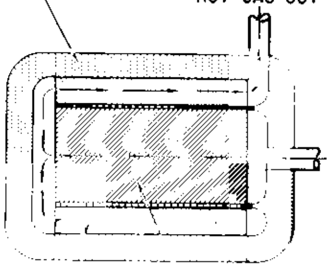

Fig. 6. Superheater reactor schematic outline.

a way that the temperature limitations of the base material can be exploited. As discussed previously this does not seem practically possible for those materials with large resonance and thermal neutron absorption characteristics, and most hope centers on NbC and ZrC, which seem to have more favorable nuclear properties. Although the resonance absorption characteristics of these compounds are relatively favorable, their thermal absorption cross-sections and moderating capabilities are such that they do not appear capable of use as homogeneous self-moderating fuel bases without requiring fuel loading to such an extent that most of their high-temperature potential is lost (see Fig. 1).

An obvious solution to this problem is to use these materials only towards the end of the coolant flow path, where the highest temperatures are desired, and rely upon other material of lower-temperature capability (e.g. fuel-loaded graphite) for the heat generation and core heat transfer structure in the first part of the flow path, and "fold" the coolant flow path so as to achieve an optimum nuclear configuration for the high temperature material of interest. Figure 6 shows one possible arrangement for such a "superheater" reactor. The reactor core is cylindrical, surrounded with a neutron reflector, and has a moderating fuel-loaded graphite structure in the central region and a high-temperature fuel-loaded carbide structure in a shell around the graphite core. The carbide superheater section is not self-sustaining (i.e. critical) alone but is driven as an exponential pile by neutrons from the reflector and from the graphite part of the core, where perhaps $\frac{2}{3}$ of the total fission energy may be generated. In this system coolant flow is folded, first through the central core, then through the carbide shell. Criticality calculations indicate that fuel concentrations of the order of 1 per cent by volume in the carbide are sufficient to achieve the power density distributions desired for high temperature performance.

Assuming reactors can be designed around the superheater concept discussed above and with very low structural loading, it would be possible to operate PTC converters from solid-fuel source temperatures roughly at the levels given in Table 3.

Table 3. Estimated Maximum Performance of Solid Nuclear Fuel Sources: Graphite with Moderate Fuel Loading (up to 20 *per cent by vol.); Others with Small Fuel Loading (Below a few per cent by vol.)*

Nuclear fuel base materials	*Graphite* C	*Tungsten* W	*Niobium/Zirconium carbides* NbC and ZrC	*Tantalum carbide* TaC
Melting point, °C	3650 (sublimes)	3370	3500/3600	3900
Maximum material temperature, °C	2600/2700	3000	3300/3400	3700
Maximum coolant temperature, °C	2400/2500	2800	3100/3200	3500

If external converters are used and sink temperatures are kept very low (e.g. by oil or water cooling) Carnot cycle efficiencies of about 0·80 to 0·83 could be attained. Such a system might utilize helium or argon gas as the heat transport fluid, as considered in a recent study (Ref. 10), and be of use for ground power stations. Advanced PTC devices may achieve relative efficiencies of 0·5, thus yielding over-all conversion efficiency of the order of 0·4. For space power applications systems analyses show (Refs. 11 and 12) that minimum mass is attained with higher radiator temperatures (typically $\frac{2}{3}$ to $\frac{3}{4}$ of source temperature) and hence with lower over-all conversion efficiency. Use of liquid fuels might allow operation up to *ca.* 4200°C, and thus Carnot cycle efficiencies above 0·90 could be achieved for converter heat rejection to oil or boiling water. This is at best only an 8 per cent to 12 per cent potential gain in efficiency over the solid-fuel source limits.

For HMC linear flow systems based on Lorentz ($\bar{j} \times \bar{B}$) forces, net efficiencies for use of solid-fuel superheater sources will never exceed those cited above simply because the effective sink temperature cannot be made arbitrarily low, but is limited to the value extant at exit from the magnetic field region. This plus the fact of plasma radiation and convection losses to the channel walls make it appear unlikely that these devices will outperform potentially attainable PTC systems at any size or power.

Internal Direct Conversion Gaseous-Fuel Fission Reactors

We have seen previously that the maximum gas temperature and thus cycle temperature can be considerably greater (conceptually) in gas core systems than for solid- or liquid-fuel reactors, and we are attracted by the possibility of achieving conditions for high Carnot cycle efficiency, as well

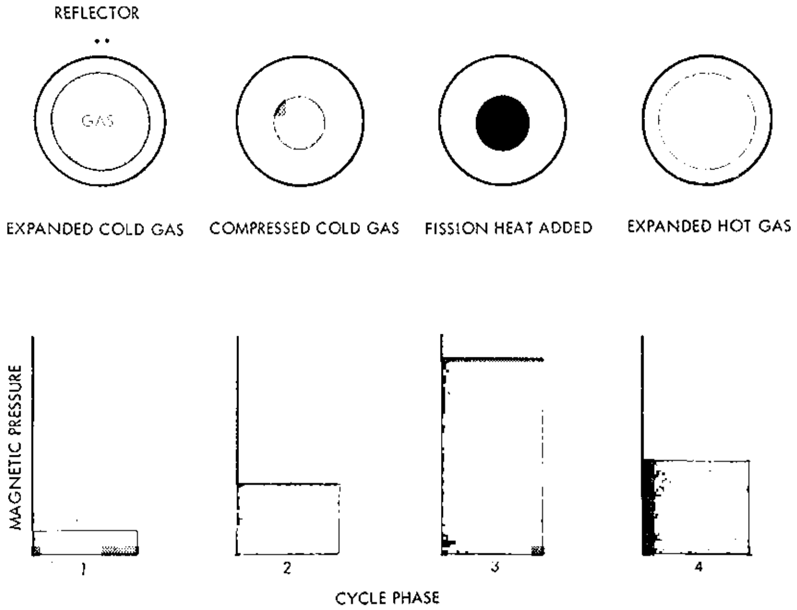

Fig. 7. Phases of the pulsing GCR cycle.

as high sink temperature. For space power use this could yield powerplant systems of relatively small over-all mass.

To achieve this we think of a gaseous core region, completely enclosed, and pulsing under the action of an externally generated magnetic field coupled with pulsed neutronic control system. Let us assume that the oscillations can be maintained stably. The gaseous core alternately expands by virtue of fission heating, and is compressed by a rising external magnetic field. The hot, ionized, core gases do work against the magnetic field in the expansion phase, and have work done on them in the compression part of the cycle. The core gases play the role of combustion gases and fresh fuel charges in conventional internal conbustion engines. If the magnetic field and neutronic control systems are properly phased, net electrical power will appear in or be delivered to the field coils and external circuit. Figure 7 shows such a system schematically at several phases of its cycle. A (P, V) diagram is sketched in Fig. 8 to correspond with the cycle points of Fig. 7.

In order to achieve maximum Carnot efficiency we tend to seek the highest possible peak gas temperature. However, one of the principal sources of loss is inherent in the pulsation process itself. This is loss due to thermal radiation from the hot gas in its compressed state, and as it expands outwards into the core void, working against the magnetic field and becoming colder with further expansion. Increased peak gas temperature will result in increased thermal radiation losses, and since these vary roughly as the fourth power of the temperature it is evident that there must be an optimum peak temperature beyond which we must pay more in radiator mass than is gained by increased "pumping" work per cycle. Although the real processes involved are quite complicated, it is a simple matter to find this optimum

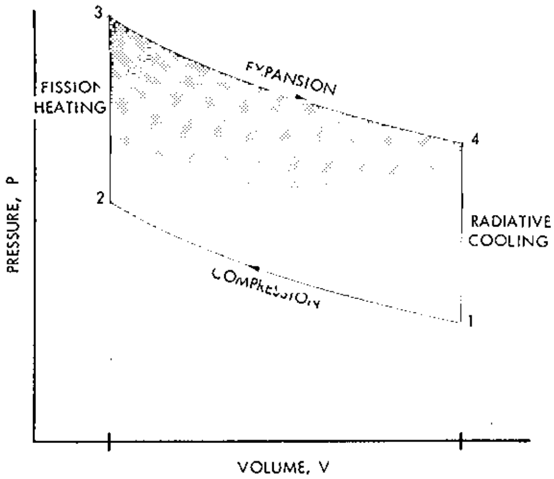

Fig. 8. PV diagram: pulsing GCR cycle.

temperature for any given system geometry for an assumed model in which the gas ball radiates always as a gray body, the core region walls are characterized by gray-body absorption, and ohmic heating losses due to field penetration into the gas ball and walls are negligible. The optimum gas temperature found under these conditions generally will be greater than the true optimum but the trends of behavior shown will be approximately correct.

Following the outline above we write the radiation loss rate from a spherical plasma ball of radius r at temperature T to walls at T_w as

$$\frac{dq}{dt} = \sigma\varepsilon(T^4 - T_w{}^4)4\pi r^2 \tag{1}$$

Neglecting acceleration forces the system pressure is simply

$$P = nkT = 82\ \mathrm{m_{crit}}T/r^3 \tag{2}$$

where $\mathrm{m_{crit}}$ is critical mass in kg, P is in atm, T in °K, and r is plasma radius in cm. At best the rate of generation of power by expansion against the magnetic field pressure P_B is just $P_B(\mathrm{d}V/\mathrm{d}t)$, or from geometry

$$\frac{\mathrm{d}e}{\mathrm{d}t} = P_B(t)\,\frac{\mathrm{d}V}{\mathrm{d}t} = P_B(t)4\pi r^2\left(\frac{\mathrm{d}r}{\mathrm{d}t}\right) \tag{3}$$

If we cause the magnetic field to vary in time so that $P_B \simeq P$, equation (3) becomes

$$\frac{\mathrm{d}e}{\mathrm{d}t} = 4\pi P^2 m_{\mathrm{crit}} T\left(\frac{\mathrm{d}\,(\ln r)}{\mathrm{d}t}\right) \tag{4}$$

Now, assuming that irreversible radiation losses [equation (1)] are small during the expansion and compression phases we can approximate these phases by a polytopic law of the form

$$PV^n = \text{constant} \quad \text{or} \quad TV^{n-1} = \text{constant} \tag{5}$$

The latter statement gives a relation between temperature and core plasma size. With this we can eliminate one of the two variables (r and T) in the power equation (4) and find the useful power output by integration of

$$\frac{\mathrm{d}e}{\mathrm{d}t} = -\{4\pi[82 m_{\mathrm{crit}}/3(n-1)]\}\,\frac{\mathrm{d}T}{\mathrm{d}t} \tag{6}$$

over the paths 1–2 and 3–4 shown in Fig. 8. In the absence of radiation losses the (Carnot) efficiency would be simply $(\Delta e_{34} - \Delta e_{12})/\Delta e_{34}$. The true efficiency will be less than this because of thermal and nuclear radiation losses to the walls over the cycle. To estimate thermal losses along paths 4–1 and 2–3 (i.e., at the constant volume conditions) we must integrate equation (1) directly, subject to the constraints that

$$c_p m_{\mathrm{crit}}(T_4 - T_1) \equiv \int_{t_4}^{t_1} \mathrm{d}t\,(\mathrm{d}q/\mathrm{d}t) \tag{7a}$$

and

$$c_p m_{\mathrm{crit}}(T_3 - T_2) \equiv \int_{t_2}^{t_3} \mathrm{d}t\,(\mathrm{d}q/\mathrm{d}t) \tag{7b}$$

Carrying out these calculations we find

$$\Delta e_{34} = \{4\pi[82 m_{\mathrm{crit}}/3(n-1)]\}\,\Delta T_{34} \tag{8a}$$

$$\Delta e_{12} = \{4\pi[82 m_{\mathrm{crit}}/3(n-1)]\}\,\Delta T_{12} = \Delta e_{34}(T_1/T_4) \tag{8b}$$

Where we have used the constraint that $(r_4/r_3) = (r_1/r_2)$, thus $(T_3/T_4) = (T_2/T_1)$ or $\Delta T_{34} = \Delta T_{21}(T_4/T_1)$, which yields a reversible-system (Carnot) efficiency of $\eta_c = (T_4 - T_1)/T_4$. Making use of the energy balance equation (7), irreversible losses in the actual cycle are found from

$$\Delta q_{41} = c_p m_{\mathrm{crit}} \Delta T_{41} = \sigma \varepsilon 4\pi r_4^2 \int_{t_4}^{t_1} \mathrm{d}t\; T(t)^4 \tag{9a}$$

$$\Delta q_{23} = c_p m_{\mathrm{crit}} \Delta T_{23} = c_p m_{\mathrm{crit}} \Delta T_{41}(T_3/T_4) = \Delta q_{41}(T_3/T_4) \tag{9b}$$

and by integration over the paths 3–4 and 1–2. To carry out this latter we must know the rate of expansion of the gas plasma. Taking this as $r = R_0[1 - \alpha \cos(\omega t)]$, and using $T = T_3(R_3/r)^{[3(n-1)]}$ we can integrate equation (1) over the time $\Delta t_{34} = (\pi/\omega)$ required for expansion from R_3 to R_4. Similarly we can integrate over the compression cycle using $T = T_1(R_1/r)^{[3(n-1)]}$ and a time span $\Delta t_{12} = (\pi/\omega)$. In both cases it is found that Δq_{34} and Δq_{12} vary inversely with the expansion/compression frequency ω thus, in principle, we can reduce radiant losses in these phases to arbitrarily small values by postulating operation at arbitrarily large frequencies of motion. Note that this does not necessarily imply large overall cycle frequency. Rather, if ω is very large, the over-all cycle frequency will be set principally by the radiating time required along paths 4–1 at the cold/expanded end of the cycle. This is found by solution of the differential equation

$$\frac{\mathrm{d}T}{\mathrm{d}t} = \left(\frac{\sigma\varepsilon}{c_p m_{\mathrm{crit}}}\right) 4\pi r^2 T^4 \tag{10}$$

for $T(t)$ at constant radius r, yielding

$$\Delta t_{41} = \frac{c_p m_{\mathrm{crit}}}{3\sigma\varepsilon 4\pi r_4{}^2 T_1{}^3}\left[1 - \left(\frac{T_1}{T_4}\right)^3\right] \tag{11}$$

Small Δt_{41} (hence high frequency of operation) is favored by large sink temperature T_1 and high plasma emissivity ε.

Assuming Δq_{34} and Δq_{12} are negligible (i.e. high-speed expansion/compression) we can assess the upper limit on the potential efficiency for such a pulsing-gas-core direct conversion system. This will be simply

$$\eta_{\max} = (\Delta e_{34} - \Delta e_{12})/(\Delta e_{34} + \Delta q_{23} + \Delta q_{41}) \tag{12}$$

Combining previous expressions for these we find

$$\eta_{\max} = \frac{\left(1 - \dfrac{T_1}{T_4}\right)}{1 + C\left[\left(1 - \dfrac{T_1}{T_4}\right)\left(1 + \dfrac{T_3}{T_4}\right)\Big/\left(\dfrac{T_3}{T_4} - 1\right)\right]} \tag{13}$$

Where the coefficient is $C = 3(n-1)c_p/4\pi(82)$ with c_p in units of 10^{-6} (erg/kg °K) to match the units of equation (2). Returning to equation (2) we can show that the coefficient can be reduced directly to $C = (c_p'/k)(n-1)$ where c_p' is the specific heat per atom or particle in the gas (number of particles assumed constant). Using this and writing temperature ratios as $(T_a/T_b) = T_{ab}$ we have

$$\eta_{\max} = \frac{(1 - T_{14})(T_{34} - 1)}{(T_{34} - 1) + (c_p'/k)(n-1)(1 - T_{14})(T_{34} + 1)} \tag{14}$$

In the limit of T_{34} infinitely large and T_{14} zero this becomes $\eta_{\max}$ (limit value) $\simeq [1 + c_p'(n-1)/k]^{-1}$. At ultra high temperature the effective specific heat per plasma particle (heavy ion and electron) may be $c_p' \sim 2k$ to $3k$

(including effects of ionization) thus η_{max} (limit value) may be $1/[1 + 2(n-1)]$ to $1/[1 + 3(n - 1)]$. For $n = 5/3$ (as for a monatomic ideal gas) we have η_{max} (limit value) $\simeq 0{\cdot}43$ to $0{\cdot}33$. For more realistic limiting temperature conditions $T_{14} = 0{\cdot}3$, $T_{34} = 5$, we have maximum potential overall efficiencies of only 0·29 to 0·23. This type of system does not seem to offer promise for highly efficient energy conversion hence may not be competitive for future ground-based power systems where high efficiency can be obtained by use of low sink temperature. However, it may be found useful for space power systems (where mass is important) because of its very high sink-temperature capability, which can yield low-mass radiators.

Considerations similar to those above lead to qualitatively similar conclusions with respect to the potential efficiency of fusion power generation.

CONCLUSIONS

It appears unlikely that solid fuel nuclear sources will yield cycle temperatures much above 3000°C. At this level direct conversion by PTC systems external to the source, using an inert gas for energy transport, potentially can yield Carnot efficiencies above 0·8 for ground power systems. Assuming 0·5 relative efficiency in the converters this may eventually result in 0·4 efficient ground power stations. The same type of system operating at optimum conditions for space use could achieve Carnot efficiencies of only 0·25 (Refs. 11 and 12) and net efficiency of roughly 0·10 to 0·15. Ultra-high-temperature gas core reactor systems seem unpromising for ground station use on grounds of efficiency but, because of their inherent high sink temperature capability may be up to twice as efficient (net) as advanced solid-core systems for space power use. Fusion-plasma direct-conversion systems (if proven feasible) do not seem to show any greater promise than do gaseous fission systems, but are of interest for other reasons (availability of fuel).

SYMBOLS

$C = 3(n - 1)c_p/4\pi(82)$
m_{crit} = critical mass
P_B = magnetic field pressure
P_c = system pressure of cavity
R_c = radius of gas-filled cavity
T_m = maximum possible operating temperature
T_w = temperature of walls
c_p = specific heat at constant pressure
c_p' = specific heat per atom or particle
n = ratio of specific heats
n_F = nuclear fuel density
q_c = coolant heat flux capability
r = radius of spherical plasma ball
ε = plasma emissivity
$\bar{\varepsilon}$ = effective value of plasma emissivity
η_G = Carnot cycle efficiency

η_{max} = upper limit on efficiency for a pulsing-gas-core direct conversion system
ω = expansion/compression frequency
σ = Stefan-Boltzmann constant

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DISCUSSION

W. Oldekop (Siemens-Schuckertwerke AG., Erlangen, Abteilung Reaktor-Entwicklung):

In connection with the paper of Dr. Bussard on "Nuclear Source Limitations for Direct Conversion Devices", I would like to make some remarks on the suitability of various reactor systems with thermionic energy conversion.

In the course of the last two years, Siemens-Schuckertwerke in Erlangen have been carrying out various design studies on reactor systems with thermionic energy conversion. The main aim of these studies was to compare the characteristics of several reactor types at various powers. Comparative calculations were carried out on six thermal and three fast reactors with thermionic converter fuel elements within the core, and on three thermal reactors with converters outside the core.

In the case of the thermal reactors with in-core thermionic energy conversion, the fuel consists of an Mo–UO_2 cermet. The Mo serves at the same time as cathode. The anodes are cooled by Na or Li-7. The moderator consists of $ZrH_{1\cdot7}$. The fuel element diameter was varied between 0·8 and 1·2 cm, and the ratio of hydrogen atoms to U^{235} atoms between 370 and 90.

The fast reactors with in-core thermionic energy conversion have a similar structure, though in this case there is naturally no moderator.

In the case of the thermal reactors with out-core thermionic energy conversion, BeO was assumed as moderator. The converters were combined with the radiator.

The following results were obtained:

With electrical powers between 20 and 100 kW, practically only thermal reactors should be considered. Fast reactors are not suitable for powers below 100 kW since their critical masses are too large.

Specific masses of around 15 kg/kW$_e$ can be achieved with thermal reactor systems with in-core energy conversion at powers of about 50 kW$_e$; the corresponding values for systems with out-core thermionic energy conversion are about 20 kg/kW$_e$ and for the turbo-electric SNAP8 system 45 kg/kW$_e$.

For powers of several hundred kW$_e$ specific masses of fast and thermal reactors are expected in the vicinity of 5 kg/kW$_e$ and 10 kg/kW$_e$ respectively. Thus in the case of in-core thermionic energy conversion thermal reactors are more favorable at lower powers and fast reactors at higher powers. However, from the financial point of view the situation becomes somewhat different. The costs are made up of fuel costs, construction costs and transport costs to the orbit. Fuel costs for fast reactors are so high that even at high powers thermal reactors having in-core thermionic energy conversion seem to be more attractive. It is our intention, therefore, to concentrate our future efforts on such systems.

R. PRUSCHEK (Institut für Hochtemperaturforschung, Technische Hochschule, Stuttgart, Germany):

I should like to make some additional comments on the specific power (kW/kg) of thermionic-nuclear reactor systems. The calculations are based on experimental data of thermionic converters in laboratory scale out-of-core tests. It should be noted that converters in the core of a reactor do not provide satisfactory performance at the present time, especially as far as lifetime is concerned. Thus, the presented results of calculations on specific power are to be regarded as optimistic values, which may be obtained some day.

Considering nuclear reactors, the temperature in the core is limited by the materials used. It is generally accepted that at the present time the emitter temperature should not be higher than 1800°C. Most reactor designers would prefer a temperature even less than 1800°C.

Assuming this temperature and the power density of 10 W/cm^2 as well as an efficiency of 10 per cent as practically feasible, calculations may be performed on specific weight resp. specific power of an electricity generating device composed of a nuclear reactor, thermionic converters and all auxiliary equipment, including radiator.

These calculations are of a rather complex nature, which results from the big variety of parameters. First of all, it is necessary to state the requirements, i.e. to distinguish between systems for auxiliary power and systems for electrical propulsion. In the latter case, the square root of the utilizable specific energy contained in the power generating system is proportional to the terminal velocity. This means, burnup of the reactor fuel becomes a critical parameter for the reactor lay out.

Due to the above-mentioned big variety of parameters, it is not easy to judge whether the thermal or the fast reactor with in-core thermionic converters will better meet the requirements.

Fast reactors allow a higher temperature in the coolant, since there is no moderator which limits the temperature. This is, of course, only true if the moderator constitutes the temperature limiting component. Otherwise, the thermal reactor would allow a higher coolant temperature, due to the fact that the melting point is lowered with increasing uranium content in a fuel mixture composed of refractory materials and uranium carbide. This means, the radiator becomes smaller, but the fuel inventory for a fast reactor is rather high. Coolant temperature in a thermal or epithermal reactor is limited by the moderator, for example for zirconium hydride, the radiator becomes big and heavy, but fuel inventory is much smaller than in the case of the fast reactor. For this reason, the decision, whether thermal or fast reactors better meet the requirements, depends on the cost for placing the power plant into the orbit.

Summary

Reactors with in-core thermionic converters may attain specific powers of the order of 0·2 kW/kg to 0·3 kW/kg depending on the power level To expect 0·1 to 0·2 kW/kg in the near future would be more realistic. Application of fast or thermal reactors depends on the ratio of transport cost to fuel cost and—which is important—on the power level. The out-of-core type (fast reactor) with homogeneous solid core surrounded by thermionic converters shows even lower specific power and high fuel inventory; however, no coolant loops and pumps are needed. This type may be applicable within a limited power range—we assume, for small powers.

Burnup as well as the shielding problem were not considered in our calculations so far. Specific power will be lower, if high burnup has to be taken into account, which is required for electric propulsion power supply and long missions.